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13. ABSTRACT (Maximum 200 words)  A microwave-driven source of negative hydrogen ions was assembled and tested at Berkeley. The source consisted of two regions, each with separate plasma conditions. The purpose of this test was to simulate the conditions for optimized negative hydrogen yield reported theoretically by Hiskes at Livermore. Experimentally, the ion yield followed the general trend of Hiskes' theory, but additional yield was seen by surface conversion processes on the barium cathode.					
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## 0. INTRODUCTION

High current density  $H^-$  sources are required for the development of MeV range neutral particle beams. The relative advantage of  $H^-$  sources over more conventional  $H^+$  sources, which are already available in the multiampere range, is that the neutralization efficiency of  $H^-$  remains usable in the MeV range, whereas the efficiency of neutralization of  $H^+$  falls to zero as the particle energy increases above 100 KeV.

Negative hydrogen production is possible in a finite volume by two channels. First, volume production can occur in a bulk plasma within the source region. Second, surface production can take place on the walls of the source. Surface production is enhanced by the presence of low work function materials on the walls, such as cesium or barium. These, however, may be undesirable from the viewpoint of the reliability of the attached accelerator, particularly in a low-maintenance environment such as a space platform. While most high-current  $H^-$  sources exploit surface production to some extent, there is still a strong incentive to develop high-yield volume production  $H^-$  sources.

Volume production of  $H^-$  is a two-step process. The rate coefficients for both electron attachment to hydrogen atoms and for dissociative attachment to ground-state hydrogen molecules are small. However, there are very large cross sections, and thus rate coefficients, for the dissociative attachment of  $H_2$  molecules in vibrationally excited states, with nonzero rotational angular momentum. These "rovibrationally" excited molecules are labeled  $H_2(\nu'', J'')$ . These states can be generated by inelastic collisions with free electrons in a plasma.  $H^-$  production then follows from dissociative attachment reactions on free electrons. Unfortunately, the electron energies required for optimization of these separate atomic processes are quite different: the electron excitation reactions leading to higher vibrational levels require electrons with energies above 10 electron volts, while the dissociative attachment reaction rate is optimized in a thermal plasma with an electron temperature of 1.2 electron volts.

Because of these disparate energy requirements, a two-region plasma source may be optimal for volume production of  $H^-$  ions. The first region must have a plasma with temperature of 5 eV or higher. The second plasma should be relatively colder, with a temperature between 1.0 and 2.0 electron volts. The chambers should be constructed so that neutral particles can traverse freely between the two zones, so that  $H_2(\nu'')$  generated in the primary can traverse into the secondary and be converted into  $H^-$ . A general outline of requirements for a source of this kind was proposed by Hiskes<sup>1</sup>, who found theoretical yields under optimum conditions of the order of several amperes per square centimeter.

The Berkeley experiment is an attempt to provide the conditions prescribed by Hiskes in a microwave-driven plasma source. The primary zone is excited by microwaves at 2.45 GHz. A confining cusp magnetic field is generated by a set of ten samarium-cobalt permanent magnets. These magnets create a field which causes the electrons to be in cyclotron resonance with the entering microwaves in the primary chamber. The secondary side has a plasma generated by a thermionic cathode and grid assembly. The plasmas are separated by a screen assembly, which can be either a simple copper mesh screen

or a compound screen assembly with programmable voltages. Extraction is done with a straightforward biased extraction plate, and the ions are collected into an electromagnetic mass analyzer.

This experiment has been in operation since 1987 on the Berkeley campus. Data obtained from this experiment was recently presented at the International Conference on Ion Sources in July 1989. The paper will appear Review of Scientific Instruments in November 1989, and a reprint is attached to this report as an appendix.

## 1. FIRST YEAR ACCOMPLISHMENTS

During the first contract year (1987-1988) the experimental apparatus was moved from its former site at Lawrence Berkeley Laboratory to the Nucleonics Laboratory on the U. C. Berkeley campus. A new magnetron power supply was fabricated for the experiment with a power capability in excess of 1 kilowatt of 2450 MHz RF. A E-H tuner and a high-power vacuum window were added to assure reliable and efficient operation at the higher power levels. Basic studies of the source temperature and density were done with Langmuir probes. It was found that as microwave power was increased, the density was increased roughly linearly with microwave power, with a characteristic density of  $7 \times 10^{10} \text{ cm}^{-3}$  at a power level of 700 watts. Temperature was more or less constant in the discharge region as RF power was raised, however, indicating that perhaps temperature was being clamped by radiation. Plasma potential  $\Phi/T_e$  appeared to be around 5.0, which indicated the presence of a runaway or "slideaway" type of spectrum common in ECE sources. A simple electromagnetic mass analyzer was used with a circular aperture extractor operating at around 100 volts of positive extraction potential was used to detect  $H^-$  yields in the simple bucket-type geometry. In these experiments, yields were as high as  $4.0 \text{ mA cm}^{-2}$  were observed, and optimum fill pressure was found to be 4 microns. Yields were found to scale roughly as the square of microwave power, which again indicates a two-step process, since density was linear in microwave power.

Several screen geometries were then tried in order to optimize the yield from this source operating in a tandem mode. One of the difficulties encountered in the screen assembly design was the tendency for a single copper-mesh screen against the RF-heated plasma primary side to re-radiate a large amount of RF into the secondary chamber, which made it difficult to control the secondary plasma by independent means such as electron injection from a cathode. The reason for this re-radiation is that plasma electrons on the primary side of the screen are accelerated toward the screen in some places by the RF electric field. These particles could then pass through the screen and re-radiate their kinetic energy pickup every other half-cycle of the RF phase. This re-radiated energy could be substantial: while a simple RF shielding calculation in vacuum shows that the screen used should attenuate the RF by about 40 dB, the actual measured RF level in the secondary was usually within a few dB of the RF level in the primary. This problem was solved by using two screens spaced roughly 6 cm apart. The closely spaced screens then had sufficient Debye sheathing potential buildup in the area between them to prevent the excursion of RF-driven electrons from the primary into the secondary. RF loss through the combined screens was then an acceptable 20 dB or so. The penalty paid for this approach was a

reduction in the line-of-sight transparency as seen for the traversal of the desired excited molecules between the primary and secondary form around 91 percent for one screen down to around 80 percent. The additional screen material also introduced more surface area into the experimental apparatus, and was doubtless a source of undesired contaminants such as water and organics, which slowed the activation process in the cathodes. Attempts at producing a secondary plasma by emission from cold-cathode filaments resulted in very low densities in the  $10^8 \text{ cm}^{-3}$  range and showed virtually unmeasurable  $H^-$  yields given the signal-to-noise ratio of the mass analyzer.

## 2. SECOND YEAR ACCOMPLISHMENTS

During the 1988-1989 contract year, most activity centered on improvements in the extraction geometry and in improving the quality of the plasma in the secondary chamber. A series of experimental runs, as described in the attached paper, were directed at verifying key components of Hiskes's theoretical model.

The mass analyzer for this experiment was improved by the addition of a series of baffles to restrict the particle pickup at the collector to collimated particles on the circular trajectory path, with the suppression of secondary electrons and with the removal of spurious ions in higher-order orbits. A factor of 1000 improvement in the noise floor was observed following these improvements. The extraction geometry was optimized by adjustment of the spacing between critical components. In particular the extraction plate-to-analyzer entrance slit dimension was found to play an important role in the  $H^-$  extraction capability. It was found experimentally that changes in bias voltage on the extraction plate would affect the plasma potential, which has a dramatic effect on extraction capability.

A series of experiments was done to inject electrons into the secondary with a thermionic cathode. The cathodes used were indirectly heated dispenser cathodes, made by Spectra-Mat in Watsonville, California. These cathodes have an active surface composed of barium oxide in a porous tungsten matrix. The cathodes require an extremely clean vacuum system in order to activate, however, once activated, they were found to be quite stable and not affected by hydrogen gas of standard purity. In the first series of experiments, the cathodes were placed in the system near the extraction hole without an accelerator grid. Little electron current was generated this way, although a tremendous increase in  $H^-$  production was seen due to surface production on the BaO cathode surface. Later experiments used an accelerator grid to extract on the order of one ampere of electron current. For these experiments, the dependence of  $H^-$  production on secondary plasma temperature and primary plasma microwave power showed clear signs of the volume  $H^-$  production following Hiskes's model. While the total yield currents were relatively modest, these yields were found on a mass analyzer which was optimized for high resolution and electron suppression. This analyzer is inherently inefficient, and actual  $H^-$  currents were probably much higher.

These studies are useful for high-current source development because the relative yields can be found for a range of parameters, and thus some knowledge of the atomic physics can be obtained. This data thus forms the basis for design of a high current source.

It is likely that the RF discharge plasma is very rich in vibrationally excited  $H_2$  molecules. Evidence of this is twofold. One is the high value of the dimensionless coefficient  $\Phi/T_e$  for the primary plasma. This number is typically  $2 \rightarrow 3$  for a maxwellian plasma in electrostatic confinement. Measurements of this parameter in the Berkeley source range as high as 6.0 . This indicates the presence of a high-energy electron component, such as runaways. Thus, the electron energy spectrum is somewhat harder than the 5.0 eV measured temperature would indicate. This in turn means that the portion of the electron population with energies above 10-15 eV is larger than one would expect in a maxwellian distribution, and thus electrons with enough energy to cause collisional excitation of the higher  $\nu$  levels are rather prevalent.

A second reason for expecting a large vibrationally excited population is that a strong peak in  $H^-$  production is seen as a function of fill pressure. This indicates that a two-step rate process is involved, with the basic rate equations including a production and destruction mechanism. In Hiskes's theory, neutral monomers  $H_0$  play a scavenger role, in that they tend to de-excite the  $H_2(\nu'')$ . Production of neutral atoms mostly occurs on surfaces in small systems such as ion sources, and is a large effect on very hot surfaces ( $T > 1000^\circ \text{ C}$  ). An advantage of RF-driven sources over filament-driven sources is the absence of a large amount of exposed thermionic surface at high temperatures. However, as we see in the attached journal article, the introduction of a cold barium oxide dispenser-type cathode has a dramatic effect on *increasing* the  $H^-$  yield, so that perhaps the effect of increase  $H_0$  atom population when this cathode is heated remains masked by the additional surface conversion. Nevertheless, this effect is probably detectable with heated tungsten cathodes, where additional surface conversion is low.

### 3. OVERVIEW AND CONCLUSION

The results as described in the attached *Rev. Sci. Instrum.* paper show clearly that surface conversion on the barium cathode was a factor in increasing the overall  $H^-$  yield. However, this cathode surface material has many desirable engineering properties which make it a better candidate for surface conversion sources than the usual cesiated or bariated materials. Firstly, the barium compound is embedded in a tungsten matrix, and thus does not have the oxidation problems associated with other materials. Secondly, the material can be renewed simply by heating it to the temperature at which the barium oxide is mobile and re-coats the surface of the material. Thirdly, there is substantial experience in machining this material into arbitrarily large (tens of cm) pieces suitable for negative ion sources. Entire assemblies currently fabricated from stainless steel and copper could be made from tungsten dispenser cathode material, and the barium surface could be kept alive with microwave power. Hydrogen scrubbing would result in a continuous renewal process, thus resulting in long, maintenance-free service life. This material is currently used in microwave tubes for satellite use where guaranteed performance for periods as long as seven years is required, and thus is an obvious candidate for satellite-based  $H^-$  sources.

As a suggestion for future work, it is strongly recommended that an RF-driven source be tested side-by-side with similarly sized bucket-type sources with filament heating in order to view the relative merits or drawbacks of this source type in a controlled way. Operation of this source at extraction voltages at the 30 kilovolts or so used in production sources may produce much more encouraging results than the 100 volt extraction potentials used here. The extraction potential used in these experiments was limited by the insulators and feedthroughs used and by safety-code restrictions, as this experiment was operated in an open, unsupervised area by graduate students.

Furthermore, as the premise for all volume-type source development is the population of rovibrationally excited  $H_2(\nu'')$ , and a measurement technique for measuring these vibrationally excited levels now exists using VUV absorption spectrometry, it would be beneficial to find a level population for an RF discharge of this type using the VUV technique. Experimental evidence based on probe potentials and correlation of yield with density suggests that the two-step volume process is in operation *in addition* to surface production even at  $10^{11}$  densities, and would thus be much stronger at  $10^{14}$  density. The factor of 100 or so between surface production and volume production at the densities used here would become an order unity factor at, say  $10^{13} \text{ cm}^{-3}$  densities if the scaling laws hold true to that density.

While these studies indicate that surface conversion via barium oxide cathodes is strong process, and is potentially exploitable for the production of robust surface  $H^-$  sources, the conclusion of this research is that volume production processes, if properly controlled, could enhance the yield of surface sources by a factor large enough to be worthy of consideration for the large sources required for NPB applications or for the rather similar requirements for fusion neutral beam injectors.

#### 4. REFERENCES

1. J. R. Hiskes, *Comments At. Mol. Phys.* **19**, 59 (1987).
2. G. C. Stutzin et. al., *LBL-26975*, Lawrence Berkeley Laboratory, also *Rev. Sci. Instrum.* **61**, 619 (1990).
3. M. M. Marinak and E. C. Morse *Rev. Sci. Instrum.* **61**, 508 (1990).

# A tandem microwave-driven negative ion source: Experimental results

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(Presented on 12 July 1989)

A tandem microwave-driven plasma source for the production of  $H^-$  ions has been developed and tested. The source has a microwave-driven primary chamber with a thermionic cathode-driven secondary plasma. This source was used to experimentally verify certain aspects of a theoretical model of  $H^-$  production by Hiskes. A general agreement with the theory was found for the dependence of produced  $H^-$  current with the plasma electron temperature. In addition, it appears that a surface production mechanism on the BaO-impregnated cathode enhanced the  $H^-$  current production. Experimental results are given and compared to present theoretical understanding.

## INTRODUCTION

Using a theoretical model developed by Hiskes at LLNL,<sup>1</sup> optimum negative ion production is obtained when vibrationally excited hydrogen molecules are generated in a hot-electron plasma and then allowed to enter a colder plasma where the molecules undergo dissociative attachment. The Berkeley experiment is an attempt to verify this model experimentally, and to address some technical issues of operation of a source of this kind as an ion source for an accelerator.

## I. EXPERIMENT DESCRIPTION

The Berkeley negative ion source experiment uses a tandem microwave cusp system. A schematic drawing of this source is shown as Fig. 1. There are two plasma regions in this device. In the first, a plasma with a suprathermal electron component is generated by means of a gyroresonant microwave discharge. A screen separates this region from a second, colder region of plasma generated by a thermionic cathode. Neutral particles can traverse from the primary zone into the secondary.

The microwave radiation is produced by a 2.45-GHz magnetron. It is coupled to the plasma chamber by a  $TE_{10}$  waveguide assembly which includes an isolator,  $E-H$  tuner, and vacuum window. Gyroresonance with the confining decapole cusp field allows for efficient absorption in the plasma electrons. Electrons are gyroresonant on a surface of constant  $|B| = 875$  G, which is a cylindrical zone of radius  $\approx 7.5$  cm.

$H^-$  ions are extracted from the plasma through an aperture (on the axis of symmetry) in a plate separating the secondary chamber from the analyzer chamber. The plate is biased at a potential near that of the secondary plasma, while the spectrometer, nearly flush with that plane, is biased near  $+100$  V. Equipotential surfaces with potentials greater than the plasma potential resembling those of a dipole are created in the chamber, allowing cold  $H^-$  ions to escape the plasma. The spectrometer has a  $1 \times 10$  mm<sup>2</sup> entrance slit for the mass analyzer. Some baffling was added to intercept stray particles, and a double collimator was added for improved optics. The external cabling was sheathed to avoid pickup from stray charged particles. These modifications re-

sulted in more than three orders of magnitude improvement in the spectrometer's ability to resolve  $H^-$  ions from secondary electrons, compared to earlier designs.

The secondary plasma was generated by a thermionic cathode. The cathodes used were indirectly heated dispenser cathodes with barium oxide dispersed throughout a porous tungsten matrix. These cathodes were cylindrical and had a 25.4 mm diam. Since the cathode is indirectly heated, the emitting surface can be maintained at a uniform potential, yielding a relatively monoenergetic electron beam.

## II. EXPERIMENTAL RESULTS

Figure 2 compares the  $H^-$  yields for various microwave power inputs and a hydrogen gas pressure of 19 mTorr, without the cathode present in the secondary chamber. The  $H^-$  yield is roughly linear with microwave power input for a magnetron current greater than 100 mA. This corresponds to a magnetron output of  $\approx 250$  W. Measurements of the plasma temperature and density in the gyroresonant chamber with a Langmuir probe revealed that at a fixed neutral pressure the plasma temperature was nearly independent of microwave power and that the average plasma density was approximately proportional to microwave power. Optimum  $H^-$  yield was seen at a gas pressure in the primary chamber of 11 mTorr.

Following the installation of the BaO cathode, an immediate dramatic increase in  $H^-$  yield was observed. This increase was more than an order of magnitude and was independent of the cathode temperature or cathode emission current. The peak  $H^-$  current detected was 790 nA, corresponding to a current density of  $8 \mu A/cm^2$ . The actual cur-

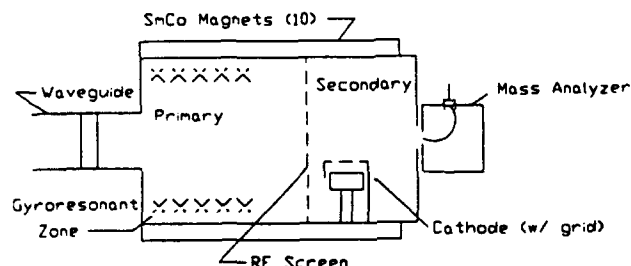


FIG. 1. Schematic diagram of experimental setup.

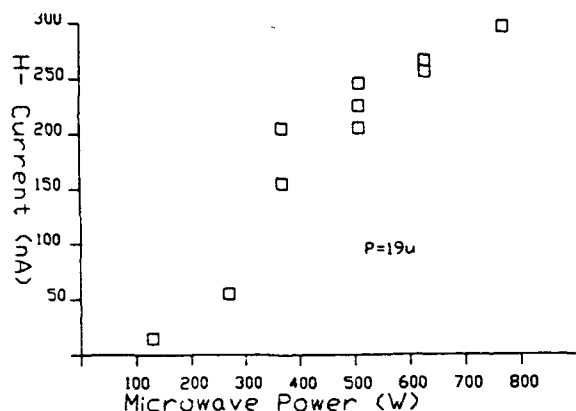


FIG. 2.  $H^-$  current vs microwave power with the cathode not installed.

rent extracted is of course considerably higher since the ion mass spectrometer is an inherently inefficient device. The dramatic increase in  $H^-$  was independent of the cathode temperature or emission current. That is, its occurrence coincides with the mere presence of the cathode. This would tend to indicate that a surface production mechanism for  $H^-$  on the BaO impregnated tungsten surface is responsible for the observed increase in  $H^-$  concentration.

A grid was added to the cathode assembly to increase the space-charge-limited cathode emission current. The grid was mounted on a ring which was welded to bars attached to the structure via ceramic standoffs. This allowed the grid to be grounded while the bias of the cathode was varied independently. The spacing between the grid and cathode surface was approximately 1.5 mm. The grid added to the area contacting field lines in the weak field region, further raising the plasma losses, increases the plasma potential and thus reduces the  $H^-$  yield somewhat. A liquid-nitrogen cold trap was added to the plasma chamber to compensate for the necessarily low conductivity through the extractor to the diffusion pump. With the addition of the cold trap the base pressure of the system, measured in the analyzer chamber, could reach as low as  $7 \times 10^{-7}$  Torr. At this point the BaO cathode was successfully activated; an emission current of 600 mA in vacuum was measured with a bias voltage of  $-100$  V and a cathode surface at  $1075^\circ\text{C}$  (measured with an optical pyrometer). This is consistent with the Child-Langmuir current limit. It is assumed that the fraction of emitted electrons which escape the grid is approximately equal to the optical transmittivity of the mesh (70%). With a plasma the emission current could increase as high as 800 mA for the above parameters. Figure 3 shows the variation of  $H^-$  yield with hydrogen pressure with the grid assembly installed. Peak yield occurred with a gas pressure of 8 mTorr. Figure 4 shows the  $H^-$  current yield as a function of cathode bias for various neutral gas pressures. When the cathode was biased at 0 V, no current was emitted. Within the fluctuation levels between measurements no change in  $H^-$  production is seen as a result of injection of electrons having energies greater than 100 eV. The cathode current at  $-145$  V was 700 mA, independent of the hydrogen pressure. Figure 4 shows no change in  $H^-$  current extracted due to electrons with energies as low as 70 eV in 5 mTorr of hydrogen or 75 eV in 10 mTorr of hydrogen. However, a

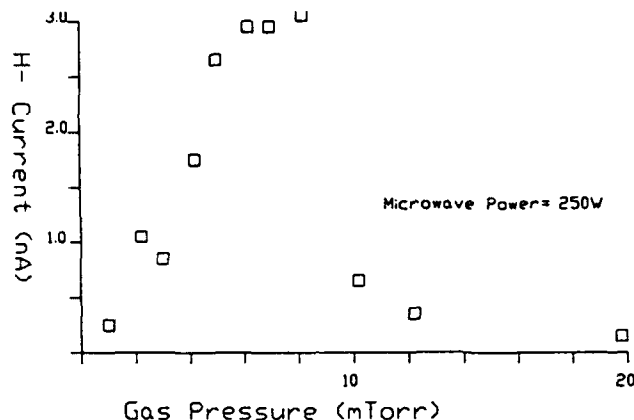


FIG. 3.  $H^-$  current vs gas pressure with the cathode assembly installed, but not energized.

marked increase in  $H^-$  current for thermionic electron energies of 30 and 60 V compared to the case with no thermionic electrons.

Measurements of current collected by the floating aperture plate versus bias were obtained. Usage of the plate as a Langmuir probe does give an average effective temperature of all electrons collected by the plate. For a 20-mTorr 500-W discharge, the inferred average electron temperature in the secondary went from 0.86 to 1.66 eV as the cathode bias was increased from 0 to 32 V. For this case,  $H^-$  yield went from 13 to 19 nA, a 46% increase. For a 250-W 8-mTorr discharge, the temperature increased from 1.22 to 1.73 eV, while the  $H^-$  yield stayed approximately constant at 14 nA.

### III. THEORETICAL MODEL

Electrons from the cathode travel across the weak field region near the axis (where they are emitted) and in the radial direction in the general direction of the converging field lines on the far side of the cross section. At some radius the condition  $\rho_e \nabla B / B \ll 1$  is satisfied and the electrons become "attached" to field lines. An estimate of the average curvature and  $\nabla B$  drift velocity for these particle orbits yields an effective time for the particle to drift to the wall of several hundred nanoseconds for a chamber width of 10 cm. This assumes no collective particle effects. At 10-mTorr pressure and a measured secondary chamber electron den-

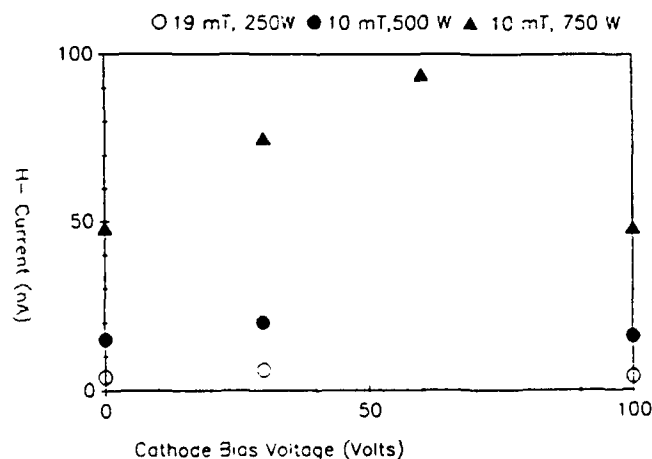


FIG. 4.  $H^-$  current vs cathode current for three primary discharge conditions.

sity of  $7 \times 10^{13} \text{ m}^{-3}$ , the effects of Coulomb collisions are negligible compared to electron-neutral collisions. In particular, ionization of molecular hydrogen and production of atomic hydrogen and excited hydrogen molecules are the reactions with sufficiently high cross sections that a sizable fraction of cathode electrons would react before being lost. For an  $\text{H}_2^+$  density of order, the secondary chamber electron density, the reaction time for a beam electron with the  $\text{H}_2^+$  for dissociation is of the order of seconds, much longer than the particle confinement time. Thus, most  $\text{H}_2^+$  are lost before they can be converted to  $\text{H}^+$  or  $\text{H}_0$ . The dissociation reaction for hydrogen molecules is most likely the dominant mechanism for slowing the beam electrons. The cross section for this reaction falls two orders of magnitude as the electron energy rises from 60 to 100 eV. Thus, a much smaller fraction of 100 eV electrons would be slowed while most 30 or 60 eV electrons would interact. This expectation is consistent with the trend observed in the data. The beam electrons produce atomic hydrogen which remains in the chamber long enough to be ionized by beam electrons or hot electrons in the primary chamber, contributing to the plasma source term.

$$n^- = \frac{\sum n_i' \langle DA\nu \rangle^i + \sum n_\pi \langle DA\pi \rangle^i + n_3^+ \langle DR_3 \rangle + n_2^+ \langle DR_2 \rangle}{\langle CD \rangle + \langle MN \rangle + (n_a/n_e) \langle AD \rangle}$$

For our plasma parameters, dissociative attachment is the dominant source term for  $\text{H}^-$ . In the low density, low temperature plasma of the secondary chamber the associative detachment term dominates in the denominator. Thus, for the secondary chamber,

$$n^- \approx n_e \left( \sum n_i' \langle DA\nu \rangle^i \right) / n_a \langle AD \rangle.$$

Since both the  $\text{H}^-$  ions and neutrals are cold, only the cross section in the numerator will vary with plasma electron temperature. The electron collisional excitation cross section is sufficiently high for the beam electron energies for an appreciable fraction of beam electrons to produce vibrationally excited hydrogen molecules. The collisional mean free path of hydrogen molecules in 10 mTorr of hydrogen is 7 cm. This is comparable to the dimensions of the system. The reaction rate for vibrational excitation of hydrogen dimers by the hot plasma electrons (5–10 eV) in the primary chamber is comparable to that for the beam electrons. Since power input through the cathode electrons is small compared to the microwave power in the primary chamber and because hydrogen molecules can move freely between the chambers, one expects the fractional increase in  $\text{H}_2(\nu'')$  produced by cathode electrons to be relatively small. Collisions which dissociate hydrogen molecules typically remove more energy

According to the Hiskes' theory,  $\text{H}^-$  is formed through three types of reactions: dissociative attachment with a rotationally/vibrationally excited state ( $DA\nu$ ); reaction with a metastable electronic state of hydrogen ( $DA\pi$ ); and dissociative recombination into ion pairs ( $DR_2$ ,  $DR_3$ ). The high energy rotationally and vibrationally excited states of hydrogen molecules are populated by interactions with hot electrons in the primary gyroresonant plasma, creating an electronic excited state of the hydrogen molecule which radiatively decays to a rotationally/vibrationally excited state of hydrogen. Collisions with thermal electrons and other hydrogen molecules produce  $\Delta\nu = \pm 1$  changes in the vibrational state, influencing the populations of the lower energy levels. Vibrationally excited hydrogen molecules are produced from ground-state  $\text{H}_2$  by inelastic collisions with electrons or on walls, or by proton transfer reactions of vibrationally excited  $\text{H}_3^+$ .  $\text{H}^-$  ions are destroyed by collisional detachment (CD), mutual neutralization (MN), and by associative detachment (AD). Thus, the overall equilibrium equation is obtained by summing over all the products of population density and cross section for each excited state. Excluding surface production,

from the electron than collisions which electronically excite the molecule. Thus, the former reaction is more effective at helping to thermalize the beam electrons. These electrons help raise the plasma temperature in the secondary which should have a marked effect on plasma  $\text{H}^-$  density according to theory.

For the 20 mTorr case described at the end of Sec. II, a substantial increase in  $\text{H}^-$  is found experimentally when  $T_e$  increased from 0.86 to 1.66 eV. The rate coefficients for dissociative attachment increase as the temperature increases over this range.<sup>2</sup> In particular, the fractional increases in the important  $\nu = 4$  and 6 rate coefficients are larger than the fractional decrease in the  $\nu = 8$  rate coefficient, which one would expect to be less highly populated. For the case of 8 mTorr hydrogen pressure, the  $\text{H}^-$  density increases very little when the cathode is forward biased. Examination of the rate coefficient curves shows that the  $\nu = 6$  curve is nearly flat in the 1.22–1.73 eV electron temperature range and that the  $\nu = 8$  rate coefficient decreases some. Thus, the general trend in the experimental data agrees with the most important features of the theoretical calculation.

<sup>1</sup>J. R. Hiskes, *Comm. At. Mol. Phys.* **19**, 59 (1987).

<sup>2</sup>J. Trow, Ph.D. thesis, University of California, Berkeley, 1983.